

Hence, the hysteresis window size can be expressed as

$$V_{hyst} = V_{TH+} - V_{TH-} = \frac{R1}{R2}(V_{OH} - V_{OL})$$

[0059] Based on the hysteresis window size equation noted above, the hysteretic window size can be adjusted by modifying the values of R1, shown as 405, or R2, shown as 410. In an embodiment, adjustment is made by substituting the fixed resistors of R1 and R2 into a potentiometer.

[0060] The low ambient-power source is modeled as an independent voltage source V_s with an equivalent source resistor R_s as shown in FIG. 4. To generate I_{sc} of 3 mA and V_{oc} of 0.9 V, we set $V_s=0.9$ V and $R_s=30052$ for the low ambient-power source model. Since the charge-strapping supercapacitor is uncharged initially, we can assume that at time $t=0$, the initial voltage is 0 V. For $t>0$, the charge-strapping supercapacitor starts to charge, and the voltage across the supercapacitor (V_{css}) can be expressed as:

$$V_{css}(t) = V_s \left(1 - e^{-\frac{t}{R_s C_{css}}} \right)$$

where C_{css} is the capacitance of the charge-strapping supercapacitor. The equivalent series resistance (ESR) of the charge-strapping supercapacitor is ignored, because it is trivial compared to R_s .

[0061] A burst controller can be implemented with the circuit shown in FIG. 6. V_{OL} denotes the low state saturation voltage, V_{OH} the high state saturation voltage, V_{TH-} the low threshold voltage, and V_{TH+} the high threshold voltage. They can be expressed as

$$V_{TH+} = \frac{R1}{R2}(V_{ref} - V_{OL}) + V_{ref}$$

$$V_{TH-} = \frac{R1}{R2}(V_{ref} - V_{OH}) + V_{ref}$$

[0062] Hence, the burst-transfer window can be

$$V_{burst-window} = V_{TH+} - V_{TH-} = \frac{R1}{R2}(V_{OH} - V_{OL})$$

[0063] The burst-transfer window can be adjusted by modifying the values of R1 or R2. This is implemented by substituting the fixed resistors of R1 and R2 into the potentiometer.

[0064] FIGS. 5A and 5B depict waveforms of reservoir supercapacitor voltage. FIG. 5A depicts waveforms of reservoir supercapacitor voltage, enable pulse, and input voltage for charging phase and hysteretic operation. FIG. 5B depicts waveforms of reservoir supercapacitor voltage, enable pulse, and input voltage for zoomed-in hysteretic charging.

[0065] In FIGS. 5A and 5B, V_{out} is the voltage waveform of the reservoir supercapacitor, V_{css} , indicated by the magenta line 510, is for the voltage from the charge-strapping supercapacitor, and En_Dis , indicated black solid line 515, is the hysteretic control signal. FIG. 5A depicts the

simulation results for 1 second, while FIG. 5B delineates only one En_Dis pulse to clearly show the hysteretic charging operation. The boost converter turns on, indicated by the purple solid line 520, and delivers the stored energy from the 3.3 F charge-strapping supercapacitor to the 25 F reservoir supercapacitor for the short duration. As soon as the 3.3 F supercapacitor voltage, indicated by the blue solid line 525, reaches the lower bound of the hysteretic window (e.g., $V_{TH-}=760$ mV), the boost converter turns off, and the ambient source starts to charge the 3.3 F supercapacitor again, up to the upper bound of the hysteretic window (e.g., $V_{TH+}=810$ mV). The charging efficiency can be maximized when the proposed hysteretic supercapacitor charger is operating at PFM mode with 50 mV hysteretic window size and $V_{TH+}=810$ mV. That is, when the hysteresis range is preset from 810 mV to 760 mV of the 3.3 F charge-strapping supercapacitor, the efficiency of the proposed hysteretic supercapacitor charger is maximized.

[0066] FIG. 6 depicts a comparison 600 of results between conventional continuous charging scheme and hysteretic charging-mode charging scheme. The comparison 600 uses a 25 F supercapacitor under 3 mA/0.9 V source. The conventional continuous charging scheme can store energy up to 18 J (1.2 V). When the reservoir voltage reaches to 1.2 V, the continuous charging method will waste the energy of source through the leakage current of reservoir supercapacitor. Alternatively, the hysteretic charging-mode charging scheme can store energy up to 78.125 J (2.5 V).

[0067] FIG. 7 depicts the boundary between charging current and leakage current, as show through the relationship of leakage offset current to reservoir supercapacitor voltage. The boundary of the proposed hysteretic charging scheme is indicated by a black solid line 705. The conventional continuous charging scheme is marked by a blue solid line 710. In addition, the black dotted-line 715 indicates the leakage current of 25 F supercapacitor, and the blue dotted-line shows the leakage current of the 1 F supercapacitor. Despite of the PFM mode, the conventional continuous charging scheme can fully charge the 1 F supercapacitor to 2.49 V, while it can only charge the 25 F supercapacitor to 1.2 V. On the contrary, the proposed charging scheme can charge the both 1 F and 25 F supercapacitor to more than 2.5 V. That is, the proposed hysteretic charging-mode dc-dc converter increases the charging offset leakage current boundary to 6.7 times at 2.5V, when compared to the conventional charging scheme. The boundary of leakage offset current could be a important parameter to evaluate the supercapacitor charger. If the leakage current of supercapacitors is on the lower side of the boundary of leakage offset current, the supercapacitor charger can fully charge the supercapacitors. Moreover, the different between the boundary of leakage offset current and leakage current of supercapacitors can improve the charging speed of the supercapacitor charger; that is, the large difference presents the supercapacitor charger can charge more quickly by offsetting the leakage current of reservoir supercapacitors.

[0068] FIG. 8 depicts a working prototype stage of the hardware architecture for the hysteretic charging-mode boost charger 800. Charger 800 includes a 25 F supercapacitor. Based on tests of charger 800, the charging rate of is faster than that of conventional MPPT-based chargers. In addition, the burst-transfer window has been explored to identify the optimal burst-transfer window size. As a result, efficiency may be improved by optimizing a burst window.